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Our ability to perceive, remember, imagine, and reason about motions is related to the mathematical constraints that are required to represent different kinds of motions and to physiological constraints that exist in motion processing. These constraints are of both a mathematical and physiological nature. Experiments were conducted that investigated the inherent differences between translations and rotations in a variety of perceptual and cognitive domains. It is concluded that rotations are harder to see, remember, imagine, and reason about due to additional complications that processing rotations requires.

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PERCEPTUAL CONSTRAINTS ON UNDERSTANDING PHYSICAL DYNAMICS

One of the fundamental tasks of spatial perception and cognition is to represent object motions. Rigid objects have six degrees of freedom in how they can move. They can translate in three dimensions and rotate about three axes. From a mathematical perspective there are fundamental differences between translations and rotations with respect to how they are represented. Translations are particle motions, meaning that representations of translations treat objects as if they were particles. Since every point within a translating object has exactly the same motion, it is sufficient to represent this object motion by describing the motion of one point within the object. Typically, the object's center of mass provides the most economical description. Rotations are extended body motions. This means that they cannot be represented in terms of the motion of a single point. Every point within a rotating object has a different motion depending upon its distance from the axis of rotation and its rotational phase. There are numerous differences between particle and extended body motions and these will be developed throughout this report. For now, we want to emphasize that particle motions manifest a fundamental simplicity that is not present in other motions. It was the purpose of the research conducted during this and the previous funding periods to investigate the implications of this difference in motion complexity for how people perceive and reason about motions.

Much of our research has been focused on the implications of the particle/extended-body motion distinction for how people reason about simple dynamical events (Proffitt & Gilden, 1989). A reoccurring theme is that people differentially appreciate the dynamical significance of translational and rotational motions; they possess a far better understanding of translations. Imagine, for example, that you are observing the behavior of a toy top. Whether or not a top is spinning, it falls straight down when dropped (translational context); however, if placed on a pedestal (rotational context) its behavior is influenced by its spin. If it is not spinning, then it falls off the pedestal, whereas if the top is spinning, then it precesses. The behavior of a top in free fall is easily assimilated by common sense, whereas the precession of a spinning top balanced on a pedestal is not. In the latter case, we are amused because the spinning top <u>looks</u> like it ought to fall even though our present and past experience with the toy informs us that it does not. We have investigated people's common-sense understandings of rotational dynamics and found them to be profoundly muddled relative to their intuitions about translational dynamics (for reviews see Gilden, 1991; Proffitt & Gilden, 1989). Two findings are of special interest. First, reasoning about rotational dynamics is not much improved by viewing ongoing events (Kaiser, Proffitt, Whelan, & Hecht, 1992). Second, people who have explicit knowledge about rotational dynamics (physics teachers) or who have considerable experience observing their behavior (bicycle racers, professional billiards players) have essentially the same common-sense intuitions about rotational dynamics as do novices (Proffitt, Kaiser, & Whelan, 1990; Hecht, 1992).

The difference in people's understandings of translational versus rotational events is due, in large part, to differences in the representations that are demanded from the observer (Gilden, 1991; Proffitt & Gilden, 1989). These differential demands reflect both mathematical and physiological constraints on motion processing.

Mathematical and Physiological Constraints on Motion Representation

Axis constraints

Translations and rotations can be distinguished in terms of what can be represented locally on the basis of correlation in space-time. Every point on a translating object undergoes the same motion; thus, if the velocity of some point on an object is detected, then the motion of the whole object is known. This is not the case for rotations. Detecting the instantaneous velocity of a point on a rotating object provides very little information about the object's motion. The direction of rotation cannot be determined from knowing the tangential velocity at a point without further specification of the position of the point relative to the axis of rotation. Neither can the magnitude of angular velocity be determined from a local velocity vector because a point's velocity is due to two factors: angular velocity and the point's distance from the axis of rotation. The axis of rotation is implicated in both direction and angular speed and local motion detection cannot establish an axis. Translations are the only motions that can be represented without the specification of an axis. The manner in which translations differ from all other motions, entails the following three discussions: (1) a review of formal models of motion mechanisms, (2) an analysis of what can be represented by these mechanisms, and (3) a description of the geometry of motion fields.

Formal Models of Motion Mechanisms. It is well known that there is a class of cells both in and outside of primary visual cortex (V1, area 17) that are selectively tuned for direction of translational motion (see Movshon, Adelson, Gizzi, & Newsome (1985) for a review). There is increasing evidence that direction selectivity in these cells can be successfully modeled through the linear combinations of spacetime separable filters (Adelson & Bergen, 1985; Watson & Ahumada, 1985). Recent modifications of this basic model have incorporated contrast gain control and an expansive power law response (Albrecht & Geisler, 1991) without changing the internal logic of the direction selective mechanism.

All models of motion detection make use of the basic notion of correlation in space-time (c.f., Adelson & Bergen, 1985). The minimum definition of a motion unit is that it connects the appearance of contrast at point (x,t) with a second appearance at point (x+dx,T+dT). In a spacetime plot these two points are displaced diagonally and we shall refer to their connection by a motion unit as a diagonal correlation. Intrinsic to the design of these simple detectors is their locality. Formally, there are several senses in which these units are local. First, the spatiotemporal interval (dx,dT) might be small, in which case the units are local in the sense of neighborhood. However, there is another sense in which these units are local which is of greater concern here. Primitive motion units correlate only two points in space-time, not three or more. Formal models of motion units in V1 that link (x,t) with (x+dx,T+dT) are not conditionalized upon activity at any other point (y,t). In this sense, these motion units are also local in the sense of identity; they correlate corresponding appearances of the same thing. Now motion units may be linked in excitatory or inhibitory ways, and there may be various types of spatial pooling. Regardless of these additional complexities, single motion units appear to be logically constructed around the notion of individual correspondence or diagonal correlation.

Representation by Correlation. Formal models of motion provide a useful point of departure for understanding the processing of rotation direction and rotation speed. Correlation mechanisms are essentially designed to respond to drifting contrast and for this reason cannot compute rotation sign unambiguously. This is clear from the geometry of rotation; the instantaneous direction of any part of the rotating object depends on the rotation phase. A single motion unit cannot unconfound rotation phase from rotation sign. In order for clockwise to be distinguished from counterclockwise, it is necessary that two or more motion units be linked together.

The sort of linkage that is required for the computation of sign of rotation is more complex than spatial pooling over the outputs of individual motion units. The kind of linkage that is required here must recognize that there is an axis of rotation and that this axis induces a coupling between spatial layout and drifting contrast. For definiteness, consider the case of a needle that is rotating clockwise about its center and that is instantaneously vertical. In this case, the linkage must represent the coupling that the top half is moving to the right and the bottom half is moving to the left. These interaction terms (couplings) are introduced by the axis of rotation and in principle cannot be rendered by simply summing over the outputs of correlators.

In addition, a rotating point's tangential speed confounds the magnitude of angular speed with the point's distance from the axis. In the case of translation, detecting the speed of one point is sufficient to specify the speed for the whole object. Detecting the instantaneous speed for a point on a rotating object does not provide information about motions of other object points; their linear speeds depend upon where they are located relative to the axis of rotation. The specification of angular speed from linear speed implicitly relies upon the representation of spatial layout rich enough to define an axis. Thus, angular speed cannot be discerned from a local space/time correlations.

It should be noted that there are cells specifically tuned for direction of rotational motion that have been isolated in the medial superior temporal (MST) area of monkey (Sakata, Shibutani, Ito, and Tsurugai, 1986; Tanaka and Saito, 1989; Tanaka, Fukada, and Saito, 1989). However, these cells occur relatively late in visual processing compared with the direction selective units that we consider here. Furthermore, the receptive fields of these cells are quite large, of order 40 to 80 degrees and it is not at all clear what relation they have to the perception of local rotation. These cells, could not, for example, process the types of motion arrays that we propose to use in our studies where individual elements often subtend less than a degree of arc. Rotation selective cells in MST seem to be more related to detecting the retinal flow associated with head tilt than to object rotation.

<u>The Geometry of General Motion Fields.</u> The comments made here regarding

rotation axes generalize to any motion field that is organized by a geometric element. Representation of motion direction and magnitude within such fields will always require the coupling of spatial relations derived from the axis into local motion directions and amplitudes. These couplings cannot be represented by additive poolings over mechanisms that respond to local energy drift. There is a taxonomy of motion fields that is supplied by the calculus of vector fields (summarized by Koenderink (1986)) which shows that all possible motion fields other than translations are organized by geometric elements. All motion fields are composed from the following four transformations which are illustrated in Figure 1:

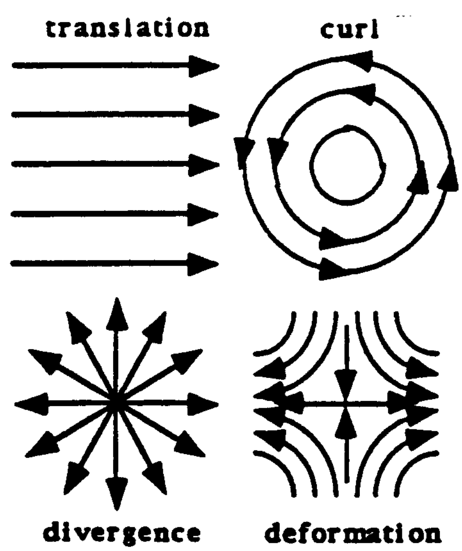

Figure 1

1. Pure translation: the rigid displacement of texture. This is the only type of flow that is not organized by a spatially distinct geometric element such as a point or an

axis. Translation may be formally viewed as a rotation about an axis at infinity, but even so, all translations will have this axis in common. Different translations are not individuated by their having different spatially located axes or points.

2. Pure divergence: the expansion or contraction of texture about a point.

3. Pure curl: rotation about an axis, shear flow separated by a line.

4. Pure deformation: expansion about one axis, contraction about an orthogonal axis. This case is distinguished from pure divergence in that the flow is volume preserving.

Thus, translation motion fields are singled out as the unique and single instance where sign and magnitude can be represented by correlation. The other motion types require the spatial localization of a geometric element, i.e. the localization of a line or a point.

Ordering Constraints

There is an additional distinction between translation and rotation that appears to be relevant to perceptual and cognitive appreciations of these types of motion. The simplest way to state this distinction is that when an object translates it goes somewhere and when it rotates it does not. Formally this distinction means that translation generates an ordered group in displacement while rotation is not. If we denote a point of departure by "0" and translation over some specified distance by $T(x)$, then $0 < T(0) < T(T(0))$ and so on. Rotation does not generate a similar hierarchy of inequalities because orientation is not globally ordered, eventually the displacement exceeds 180° and for some x, $R(R(x)) < R(x)$. Although rotation is ordered locally for restricted angles of rotation, and this ordering can be extended globally by defining angles that exceed 180°, perceptually this extension is not meaningful. The simple observation that rotation in a single direction accumulates modulo 180°, whereas translation in a single direction accumulates continuously has the following associated consequences:

1. Rotation always generates a bounded flow field and when it is about an axis internal to the body it generates a flow field that has a size on the order of the size of the body. Translation generates unbounded flow.

2. Rotations of opposite sign can map object texture to the same position. Translations of opposite sign always map texture into different positions.

3. Finite sized objects may have symmetries that prevent rotation from being detected. Finite sized objects never have symmetries that interfere with the detectability of translation.

These ideas have been articulated in a different context by Proffitt and Cutting (1980). They distinguished between object rotations and translations in terms of form and motion analysis. In essence, they argued that the perceptual system uses rotations to define what the object's 3-D structure is, whereas translations are used to specify where it is going. We make essentially the same argument here. That because translation accumulates and rotation does not, translation is a more usable source of information for appreciating event kinematics.

These inherent differences between translations and rotations have implications for all levels of processing. We have investigated these implications in the areas of detection, memory, imagination, and reasoning.

Implications of the constraints for attention

Julesz and Hesse (1970) provided initial evidence that sign of rotation is processed serially. This claim was based on the observation that a field of rotating needles divided into regions based on sign of rotation (clockwise or counterclockwise) does not effortlessly segment and perceptual boundaries do not form between regions. Subsequently, Gilden and Kaiser (1992) conducted a visual search experiment using reaction time to probe processing time as a function of the number of rotating elements. They found evidence for a serial process and that rotating needles require about 30 msec apiece for sign recognition. The evidence that direction of rotation is processed serially is in sharp contrast with the finding by Nakayama and Silverman (1986) that translation direction is processed in parallel. Nakayama and Silverman employed a standard search paradigm by assessing reaction time as a function of the number of motion elements. Their motion elements were sinusoidal waveforms contained within stationary apertures. Periodic boundary conditions were imposed so that deletion of the grating on one side of the aperture was coincident with reintroduction of the grating on the opposite side. They found that the perception of a field of translating gratings, divided into regions based on direction, will effortlessly segment and form distinct boundaries. We have verified this conjecture in numerous simulations (Gilden and Kaiser, 1992).

The distinction between translation and rotation in processing style should not be limited to the perception of sign or direction. We have conducted a pilot study in which it was demonstrated that rotation speed is processed in parallel in the following sense: a fast rotating element will pop-out in a field of slow rotating elements, but not vice versa. (This asymmetry in magnitude is common to many visual attributes [Treisman and Souther, 1985], and it was also found to hold for translating gratings.) In this pilot study, all of the rotating elements were exactly the same size. If size is equated, then the angular velocity at the objects' boundaries is no longer confounded with distance from the axis.

The collection of empirical results suggests the following theorem: Only those attributes of motions that are representable by diagonal correlation are processed in parallel. A geometric version of this theorem is that a motion attribute is processed in parallel if and only if the attribute does not require reference to a point (axis), line, or plane that organizes the optic flow.

Implications of the constraints for memory.

One of the most obvious yet significant differences between translations and rotations is that the former has a perceptible accumulation in displacement, whereas the latter typically does not. Only rotations of less than 360° have a noticeable orientation displacement; continuous rotations are cyclic, and thus, their accumulation cannot be appreciated without counting. Imagine that you are observing a rolling wheel. The wheel translates from here to there as it rotates. This displacement of the wheel is an observable product of its motion. The number of revolutions incurred during the excursion cannot be appreciated without attention to the cycling of some feature on the wheel and a counting of its cycles. In everyday situations, why would anyone want to do this? It is our contention that people pay very little attention to rotations, and for this reason, they are poorly remembered.

In earlier research we have noted that people have little understanding of rotational dynamics relative to their understanding of translational dynamics (Proffitt & Gilden, 1989; Proffitt, et al, 1990). Surprisingly, this lack of understanding is not generally characterized by biases or misinformation. Rather, people appear to have no commitments as to why things rotate the way they do. If pressed into explaining, say, why a top precesses, they will concoct some form of explanation, but their confidence in the explanation is generally quite low and is given only because it was demanded. Such explanations are not part of the corpus of beliefs that people live with, they are made up on the spot. In contrast, there is a systematicity to both the erroneous and correct ideas that people evince about translational motions (McCloskey, Caramazza, & Greene, 1980; Kaiser, Jonides & Alexander, 1986). Thus, the distinction between what people know about translation and rotation is not measured by magnitude. The distinction is deeper; people are not meaningfully engaged with the dynamical consequences of rotational motion - for the most part they do not care about it.

Consider an experiment discussed by Proffitt, et al (1990): When shown a pair of wheels (say one large and one small) and asked about which will roll faster down an inclined plane, people behave as if they have no experience with rolling objects. This is as true for physicists as it is for undergraduates in psychology courses. Of course a physicist can deduce the correct answer from the equations of motion; the point is that the physicist does not know the answer until the equations are solved. Is it the case that people do not have experience with rotation and rolling wheels? Surely not. A better hypothesis is that people do not pay attention to rotation and so behave as if they have little experience. Recent experiments by Hecht (1993) showing that people neglect rotation in making naturalness judgments about rotating wheels provides further evidence for this point of view. The consequence of not paying attention to rotation is that it is not encoded, there is no perceptual learning, no formation of expertise, nor any of the concomitant experiential benefits associated with memory.

Attentional and ordering constraints couple into each other in providing a coherent account for why people do not encode their experiences with rotation. The cyclic nature of rotation makes it inconsequential for the important task of determining where an object is going. In general rotation does not provide meaningful or useful information. Most rotations arise simply as a product of initial conditions, say when a dropped or falling object acquires some initial angular momentum. In this sense it is desirable to ignore rotation. The cyclic nature of rotation also makes it a sink for attentional resources. Thus, it is also the case that certain aspects of rotation can in fact be ignored. Rotation direction, for example, does not pop-out. In contrast, it is not possible to ignore direction of translation; the flip side of preattention is that the voluntary aspects of attention do not mediate the processing of the information. People therefore experience a certain harmony regarding rotation and translation; consequential information is delivered at no cost and inconsequential information is ignorable.

Implications of the constraints for imagined motions

The theoretical account of motion processing that we have developed is based on the idea that axes cannot be represented by motion mechanisms that effect diagonal correlation. The representation of an axis requires some elaboration of spatial layout; a form analysis that is distinct from just detection of motion. An axis of rotation and the representation of its sign minimally requires such primitive notions as top-moving-rightwards or bottom-moving-leftwards. These spatial-motion interactions are precisely what cannot be achieved by diagonal correlation.

Spatial relations such as top and bottom are only well-defined within a given frame of reference. They are relative terms and implicitly refer to the axis that gives them definition. Representation of an axis always implies the establishment of a frame of reference. The serial nature of axis sign processing is essentially a statement that axis frames are exclusive, only one can be processed at a time. All translational motions can be represented within a single frame of reference, whereas representing rotations requires a uniquely specified axis for every rotation. We shall consider cognitive understandings in environments where an axis frame must be represented in conjunction with other frames of reference.

The simplest form of the conjunction of an axis defined frame with a secondary frame is encountered in the case of a wheel that rolls without slipping. The rotational motion defines an axis that itself moves in a background environmental frame. The wheel's configuration is defined within a coordinate system that revolves about the rotational axis with the wheel. Imagine a rolling clock; its top (12 o'clock) is continuously changing its position relative to the environment but not relative to its object-centered reference frame. The secondary frame, which we shall refer to as the translation frame, is not structured by the axis. For example, the primitive spatial relations that are defined by the axis, such as the rotating wheel's top and bottom, have no meaning in this environmental frame.

A problem that we consider to be representative of those discussed under this heading is depicted in Figure 2. The reader may wish to consult their own first impressions of the number of revolutions required to traverse the line. Our own introspective assessment of this problem is that "lots of revolutions" are required. In fact, only two revolutions will bring the wheel across the line. The manifest difficulty in solving this problem appears to reside in the simple observation that it is hard to see how the rotational motion is coupled into the translational motion. Cognitively, the rotational motion is one thing and the translational motion is another thing and what the two have to do with each other is not obvious. Another way of saying this is that the two motions refer to different frames of reference and the coupling between the frames is not perceptually or cognitively transparent.

How many times will the wheel spin around
as it rolls along the line?

Figure 2

Assessment of the magnitude of the error is somewhat subtle. Hecht (1992) administered this question to a large group of undergraduates as part of a mass testing survey. He found that there was about a 15% error in overestimating the number of revolutions. (No systematic bias was found for judgments of "rolling" squares and triangles in which translational frames were appropriate to both the object- and environment-centered reference frame.) We believe that Hecht's procedure was not as sensitive to the difficulty entailed in this problem as it might have been; he assessed what people can figure out given unlimited time and not their first impressions. This is an important distinction. Hecht's methodology permitted the subjects to solve the problem at their leisure. This problem can be figured out; it does not exceed the capacities of college age adults. One way to figure it out is to mentally snip the wheel, lay it out onto the line, and evaluate how many copies of the flattened wheel are required to cover the line. We are not interested in what people can figure out; a perception-based limitation will only be manifest if people agree to disclose their first impressions.

We administered this question to 45 undergraduates as part of a class lecture. They were instructed to answer as quickly as possible on the basis of their first impressions. These instructions were repeated several times. The questions and figures were then displayed for 5 seconds on a large screen via an overhead projector. We found that there is a strong bias to overestimate the number of times the wheel will roll along the line; 2 is the correct answer while the mean response was 3.5. Our methodology is subject to the same criticism that we gave to Hecht's in that we had little control in imposing a deadline for response. In informal administrations of this problem to colleagues, we have consistently found that when harangued to give an immediate answer, most people report that 5 or 6 revolutions are required. This is quite close to the number of displacements that will cover the line.

A second problem that will illustrate the issues discussed under this heading can be appreciated by participating in the following problem: Before proceeding, cover the next paragraph since the answer is given there. Figure 3 shows two pennies in contact with each other, one placed above the other. Suppose that the top penny is rolled around the circumference of the bottom one, without slipping, until it returns to its original position. How many revolutions will the top penny make in its excursion? Answer quickly, and then take some time to think this problem through before uncovering the next paragraph.

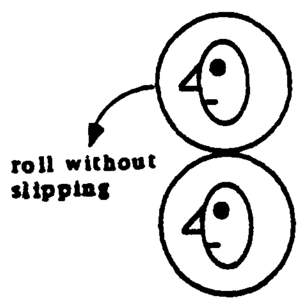

Figure 3

This is a hard problem! The answer is two. If you got this problem right, then you are exceptional as the vast majority of people will say one if prohibited from acting out the solution with real coins. What makes this problem hard is that the rotational reference frame of the top penny must be coupled with the rotational frame defined by the one on the bottom. Formally, this problem is quite similar to the apparently simpler task given above in estimating the rotations required to produce a given displacement. That is, the reference frame of rotation must be coupled with a secondary frame. In the first problem the secondary frame is translational, whereas in the second problem it is rotational.

A similar demonstration of people's inability to deal well with imaginal transformations involving multiple reference frames is seen in the work of Pani (in press). He asked people to predict the appearance of a square patch, mounted through its center on a rod, after the rod had been rotated. When the patch and the rod shared reference frames -- the normal to the patch coincided with the rod -- performance was excellent. When the patch was mounted obliquely on the rod and the rod was not vertical, performance was quite poor. Average errors were over 45 degrees.

Implications of the constraints for cognitive understandings of motion dynamics

The coupling of rotation with translation has dynamical consequences for the motions of a rolling ball. Hecht (1992) showed that people are extremely muddled about how the spin of a ball affects its trajectory. As depicted in Figure 4, the spin of a ball that is moving across a planar surface (along the z-axis) can be decomposed into three parts (Walker, 1985; Whitehead & Curzon, 1983). In keeping with conventions of billiards, spin around a vertical axis (y) is called English or side English. Spin around a horizontal axis perpendicular to the motion (x) is called follow or draw, and spin around the axis of motion (z) is called mass. Given an initial straight motion of the ball in the z-axis direction, English, follow, or draw will not change its linear trajectory, but mass will. Clockwise mass will make the ball curve to the right, while counter-clockwise mass makes it curve to the left.

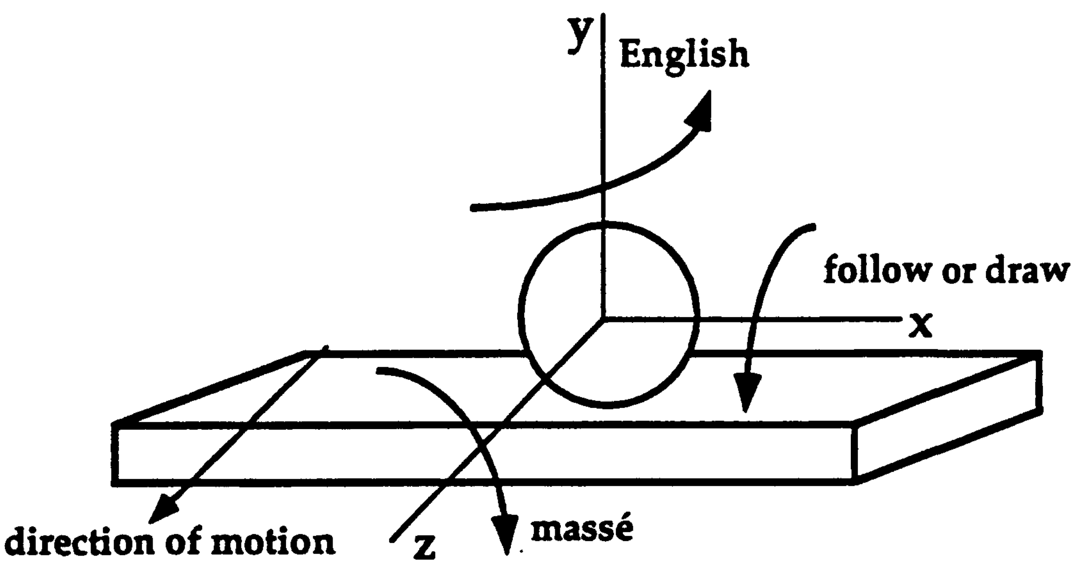

Figure 4

Hecht assessed undergraduates' predictions about how these three spins would affect the trajectory of a rolling ball and found that they did not distinguish between English and mass. In particular, they predicted that follow and draw would not affect the ball's trajectory; however, they were overwhelmingly sure that both English and mass would cause it to follow a curved path. Hecht created computer animations of this event and found that people judged as natural those paths that were typically predicted. That is, a ball with English was erroneously judged as appearing more natural when it followed a curved path than when it followed a straight one. In essence, these subjects seemed to assume that spin occurring in any direction other than that in which the ball was rolling would cause the ball to curve. Professional billiards players were also tested, and they were found to have a correct understanding of the dynamics of spin, although not surprisingly, they could not make quantitative judgments about spin's effect.

Final Progress Report

The current grant was an extension of a research program that has been funded by the Air Force Office for Scientific Research (AFOSR). The initial grant was awarded in 1987 and renewed in 1990.

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Agostini, T. & Proffitt, D.R. (1993). Perceptual organization evokes simultaneous lightness contrast. Perception, 22, 263-272.

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Summary of Aims and Results during Funding Period

Our grant application proposed four distinct sets of experiments. Significant progress was made on each and this work is summarized below.

Dynamical understandings of multidimensional systems. In this area, seven articles and chapters were published, are in press, or have been submitted. In addition, one doctoral dissertation has been completed.

The work reported in McAfee and Proffitt (1991) addressed the issue of why many people act as if they do not know that a liquid remains invariantly horizontal regardless of the orientation of its container. It was shown that erroneous judgments reflect different problem representations that people are apt to form, and that the representation that leads people to make erroneous judgments is evoked by a perceptual frames of reference bias.

Kaiser, Proffitt, Whelan, and Hecht (1992) investigated the conditions in which viewing animated displays leads to better dynamical intuitions than are evoked in paper-and-pencil tasks. They found that animation is useful only when the dynamical situation is unidimensional. This work confirms a basic tenet of our approach which is that the dynamics of multidimensional systems are not perceptually penetrable. These studies, as well as work supported by our first AFOSR grant, are summarized in Gilden (1991, 1993) and Proffitt and Kaiser (in press). These theoretical and review papers challenge current theories about people's abilities to perceive dynamical properties. It is argued that people employ heuristics when evaluating ongoing dynamical systems and that their ability to extract relevant motion information is limited by general principles of perceptual organization. A specific comparison of our account with a direct perception approach is presented in Gilden and Proffitt (in press).

Heiko Hecht (1992) has completed a Ph.D. dissertation on work support by this grant. This dissertation project investigated the understanding of rotational motions by novices and professional billiard players. (The latter were recruited and tested in Washington, D.C.). Three basic findings emerged. First, when judging wheels rolling on a horizontal plane, observers who were instructed to attend to the coupling of rotation and translation can do so; however, when judging the naturalness of wheels rolling down a ramp, observers disproportionately focused on only translation. Second, almost everyone mistakenly believes that English (spin around a vertical axis) should make a rolling ball curve. Visual animation does not improve performance. Finally, professional billiard players share some of these misconceptions. They were found to use procedural heuristics to execute their shots that do not require adequate conceptual or perceptual understandings about the dynamics of spin. These studies are currently being written up for publication submission.

Marco Bertamini (1992) completed and published his Masters thesis on an investigation on memory representations for position in dynamical contexts. He found that when shown a static image of a ball located on an inclined plane, memory for the ball's position is displaced downward.

Learning to evaluate dynamical systems. Gregory Kean completed his Master's thesis with Gilden on an investigation of the ability to judge differences and ratios within static and kinematic variables. He found that both processes of judgment exist independently for translation speed, rotation speed, numerosity, size, and angular extent. Each judgment type satisfied the axioms for the representation and uniqueness theorems to infer the existence of two independent algebraic difference structures. There was additional evidence that these judgments are linked appropriately to infer that these quantities are measured perceptually on ratio scales. These results provide strong evidence that failures in dynamical understandings arise when comparisons are made across stimulus dimension as judgments are adequate within single dimensions. This work is being prepared for publication.

The research discussed above with professional billiard players also relates to the work proposed in this section. Hecht's dissertation work showed that novices could be trained within about 15 minutes to judge the rebound trajectories of balls spinning with English and perform at this task as well as could the professionals. This finding indicates again that perceptual competencies in this domain are not particularly complex.

Path perception in both apparent and continuous motions. Hecht and Proffitt (1991) found that the apparent motion of an object that undergoes an orientation change in depth is resolved by a perceived curved trajectory in depth. This work supported the prediction made in the grant proposal that apparent motions are constrained by kinematic as opposed to dynamic constraints.

Basic issues in motion information processing. The experiments proposed in this section were completed and four articles have been published or are in press. Proffitt, Rock, Hecht, and Schubert (1992) reported a set of studies on perceiving depth from the stereokinetic effect. It was found that the stereokinetic effect - an illusion - is symptomatic of the perceptual processes that derive depth from small rigid object rotations. Similarly, Caudek and Proffitt (1993) showed that the stereokinetic effect evokes the same perceptual response as does appropriately matched motion parallax displays. A general model for perceiving depth from monocular motion information is presented in these two works. In essence, it is argued that the perceptual system extracts only a subset of the motions present in optical flow and combines this with inherent perceptual biases. Schmuckler and Proffitt (in press) showed that infants respond to stereokinetic effect displays in a manner suggesting that they perceive depth.

Finally, Kaiser and Proffitt (1992) how stereokinetic displays could be employed to reduce the computational resources required to create depth impressions in moving displays.

Conclusions

Our ability to perceive, remember, imagine, and reason about motions is related to the mathematical constraints that are required to represent different kinds of motions and to physiological constraints that exist in motion processing. These constraints are of both a mathematical and physiological nature.

Mathematics:

1. The representation of rotation, divergence, and shear motion fields requires the specification of spatial layout sufficient to characterize axes or lines at specific positions in the optic array. Only translation can be represented without reference to spatial layout. A translating body can be treated as a point particle, all other motions entail that objects be treated as extended bodies.

2. Rotation does not, in particular, generate a globally ordered sequence of displacements. More rotation does not always lead to perceptually larger angles. Angle accumulates perceptually modulo 180°.

Physiology:

Direction selective cortical motion detectors are specific to translation motions prior to the medial striate temporal (MST) area. Early neural hardware is designed to extract translation vector fields.

These constraints make translation a special case in cognitive and perceptual processing. The uniqueness of translation was investigated broadly within four areas of research.

1. Attention. Translation is processed preattentively, whereas other motion fields require focused attention. This difference arises from the requirement that a geometric element in spatial layout be specified for all nontranslational motion fields, and the positioning of a geometric element requires focused attention.

2. Memory. Translational motion is preferentially encoded and is therefore remembered better. This preference arises for two reasons; a) rotations do not accumulate as do translations, they are bounded and repetitive. b) Rotations and translations require different object representations, as extended bodies and point particles, respectively. Kinematic analysis proceeds primarily on the basis of a point particle representation; i. e. in terms of where the object as a whole went.

3. Imagination. Rotations are harder to mentally manipulate than translations. The inherent incompatibility of rotational and translational representation has implications for the ease with which they can be manipulated by thought.

4. Reasoning. Rotations are harder to understand dynamically than translations. The coupling of rotation and translation has dynamical consequences for rolling objects.

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